Development of Active and Sensitive Structural Material Systems

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Abstract

This paper describes new concepts the author has proposed and demonstrated to realize metal and polymer based sensitive and/or active structural material systems suitable for smart structures. Most of the developments have been done by simple and innovative methods without using sophisticated and expensive sensors and actuators. The following topics are mainly examined: (1) forming optical interference and loss type strain sensors in epoxy matrix simply by embedding and breaking notched optical fiber in it; (2) forming a multifunctional sensor in aluminum matrix for temperature and strain monitorings by embedding an oxidized nickel fiber; (3) fabricating multifunctional composites by using conventional structural materials - an active laminate of CFRP/aluminum of which unidirectional actuation is realized by electrical resistance heating of carbon fiber in the CFRP layer and its curvature change can be monitored using optical fiber multiply fractured in the CFRP layer.

Introduction

Smart material systems are attracting worldwide interest because of their potential uses: damage detection, health monitoring, noise reduction, vibration suppression, actuation, self repair, and fabrication process monitoring [1]. Most of these new material systems have been developed by embedding sensor and/or actuator materials in host structural materials such as polymer matrix composites [2]. Active and sensitive material systems will be able to replace or simplify complicated mechanical systems as shown in Figure 1. They will remove, for example, heavy and complicated actuation systems, hinges and tribological problems. Light-weight, high-strength and active/sensitive structural materials could be applied to many active parts for high speed vehicles such as hatches, doors, flaps and air brakes, or could be applied to innovative wings and bodies.

Figure 2 shows a major direction of the author's researches, where an active composite material with embedded functional fiber is proposed. The reinforcement fiber works as "bone" and the matrix material works as "muscle" for actuation which is controlled by stimulation and energy transmitted through the functional fibers regarded as "nerve" and "blood vessel." This material system could have a variety of functions [3].

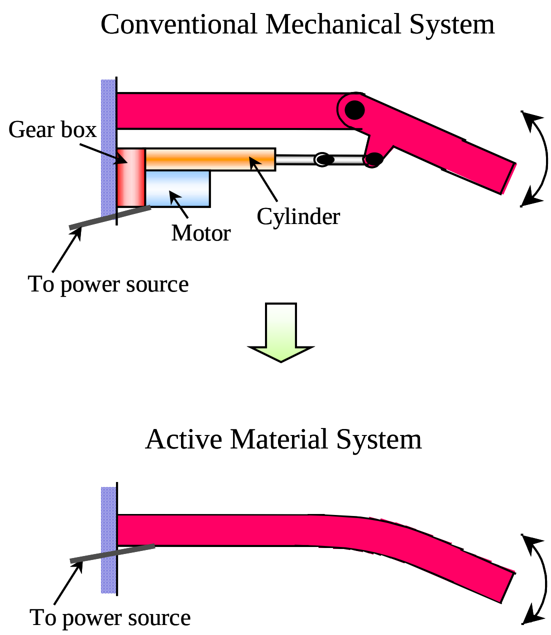

Fig. 1 Simplification of a conventional mechanical system using an active material system.

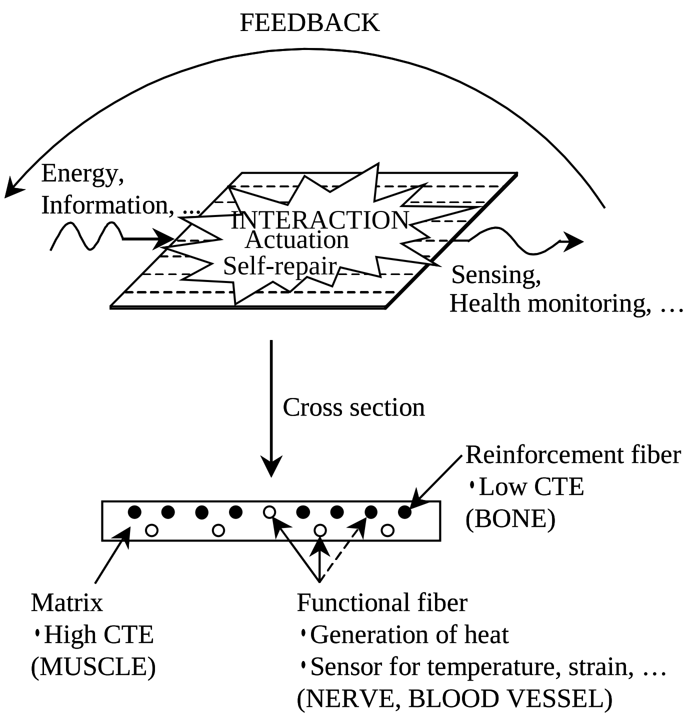

Fig. 2 An active composite embedded with functional fibers.

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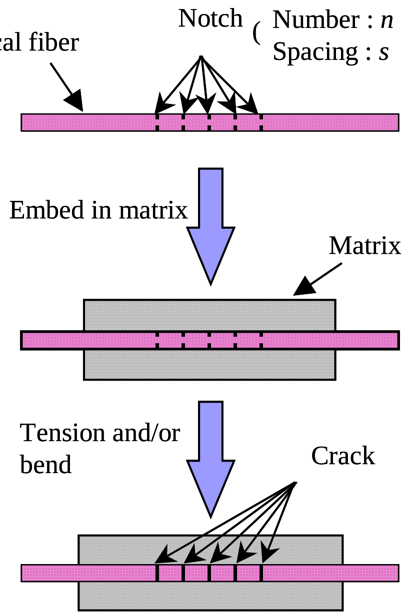

Fig. 3 The concept for in-situ formation of fiber-optic strain sensors.

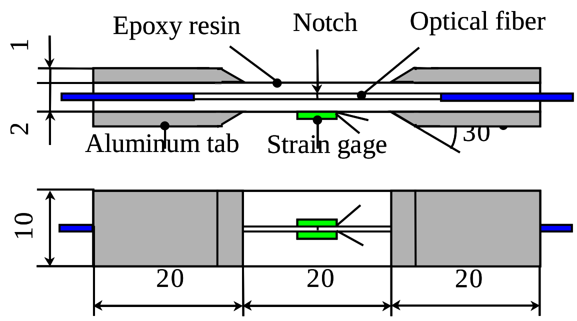

Fig. 4 The test piece of epoxy matrix embedded with a notched optical fiber for measuring optical transmission and tensile strain.

In this paper, new concepts the author has proposed and demonstrated to realize metal and polymer based sensitive and/or active structural material systems suitable for health monitoring, active shape control, and so on, are introduced. Most of the developments have been done by simple and innovative methods without using sophisticated and expensive sensors and actuators. The following topics are mainly examined: (1) forming optical interference and loss type strain sensors in epoxy matrix simply by embedding and breaking notched optical fiber in it; (2) forming a multifunctional sensor in aluminum matrix for temperature and strain monitoring by embedding an oxidized nickel fiber in it; (3) fabricating multifunctional composites by using conventional structural materials - an active laminate of CFRP/aluminum with embedded optical fiber multiply fractured in the CFRP layer.

Sensors in Structural Material

Forming a fiber-optic strain sensor in a matrix material

The author proposed simple fiber-optic strain sensors which can be formed simply by breaking optical fibers in matrix materials at notches made on the fibers before they are embedded as shown in Figure 3 [4]. In the case of a single notch (n=1), it will work as an optical interference type sensor suitable for measuring small and precise strain, and in the case of multiple notches (n>>1), they will work as an optical loss type sensor suitable for measuring large strain.

For experimental purposes, a quartz-type and single-mode optical fiber was used. An epoxy resin was selected as an example of the host materials because it is a common matrix material and because its transparency enables observation of the embedded optical fiber. Shape and dimensions of the tensile test specimen are given in Figure 4. A single notch, 5 or 15 notches, that is n=1, 5 or 15 respectively, were made on an optical fiber filament with an optical fiber cutter. The notched fiber as shown in Figure 5 was then embedded in an epoxy resin matrix. The specimen was attached in an Instron-type testing machine and the embedded optical fiber was connected to a laser diode light source of 0.67×10^{-3}mm wavelength and to a power meter. The specimen was tensile tested while the optical power variation was monitored at the constant crosshead speed of 1.7×10^{-3}mm/s.

The results of optical transmission loss L and tensile strain of a specimen embedded with a single-notched optical fiber (n=1) as a function of time are given in Figure 6, which indicates that the optical loss starts to fluctuate sinusoidally at the strain of about 0.076%, where the embedded optical fiber fractured at the notch. The specimen after the tensile test shows a crack almost normal to its optical axis as shown in Figure 7.

In the case of embedding an optical fiber with multiple notches, the specimens having 5 and 15 notches (n=5 and 15) were loaded and unloaded for five times under monitoring optical transmission. The results are given in Figure 8. During the first loading, the each embedded optical fiber fractured at the every notch. According to the experimental results, the fractured optical fibers are working as displacement sensors during the first unloading and the following loading and unloading cycles. The response is improved by increasing the number of fractures from 5 to 15.

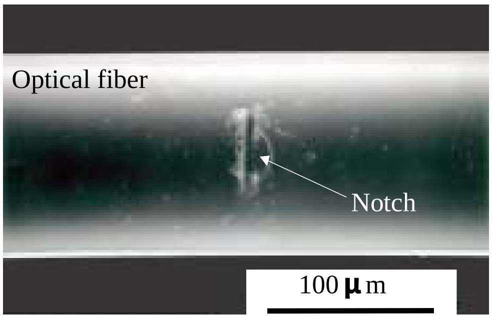

Fig. 5 An optical fiber with the notch.

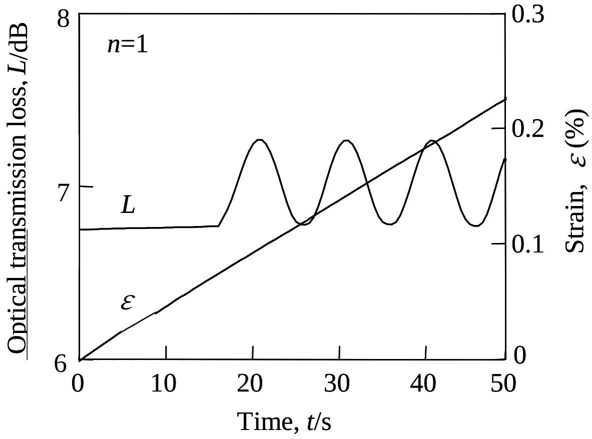

Fig. 6 Optical transmission loss and strain of the test piece during tensile test as a function of time.

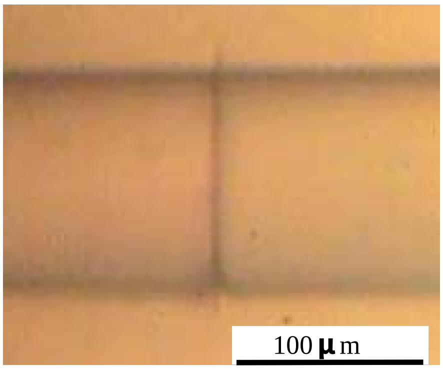

Fig. 7 An optical micrograph of the specimen with a single notch (n=1) after tensile test showing a crack in the embedded optical fiber.

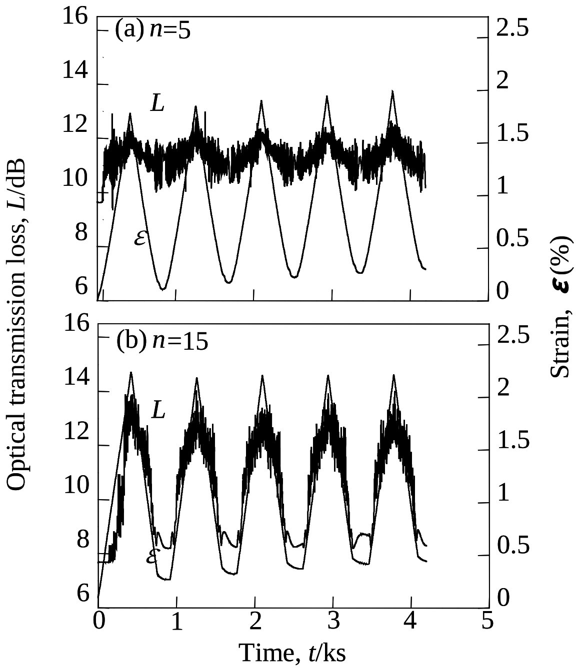

Fig. 8 Optical transmission loss and tensile strain of the epoxy matrix specimens with notches of (a) n=5 and (b) n=15 as a function of time.

With the proposed methods, compact, robust and low cost strain sensors are simply formed without the necessity of alignment of the fibers' optical axes, a tube for the alignment and an adhesive for fixing the fibers.

A simple sensor for measuring temperature and strain in aluminum matrix

Sensors for smart structural materials are not necessarily the best ones. For example, an embedded fiber filament might work as a sensor as well as a reinforcement, heater, actuator, and so on. Though carbon fiber is not the best sensor, heater, or actuator element, as an example, its versatility can make structural materials smart without an increase of cost, weight, and complexity.

Figure 9 illustrates how to create a simple temperature and strain sensor in a metal matrix [5, 6]. A pure nickel wire of 0.15mm in diameter was selected to form a thermocouple with an aluminum matrix and to form a strain gauge in it. Because the wire has to be insulated from the metal matrix, the nickel wire was oxidized at 1073K for 7.2ks in air to form a uniform NiO layer that would electrically insulate the wire from the aluminum matrix. The materials prepared as shown in Figure 10 were consolidated by hot-pressing at 798K under 16.4MPa for 1.8ks.

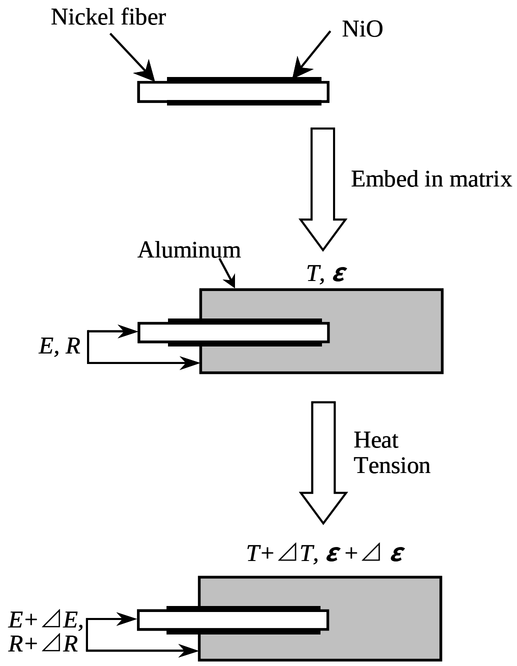

Fig. 9 The concept of a simple temperature and strain sensor in a metal matrix.

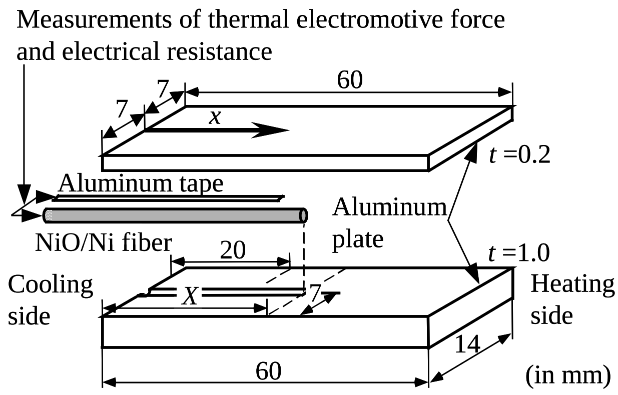

Fig. 10 Embedment of an insulated nickel fiber in aluminum matrix.

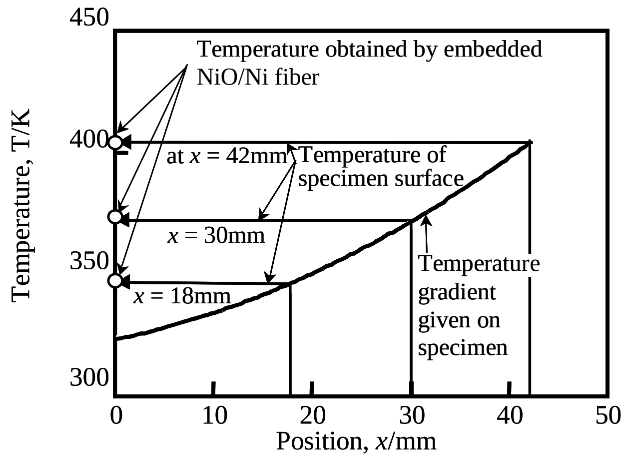

Fig. 11 Comparison of the temperature given on a sample and the temperature obtained by its embedded NiO/Ni fiber at *x* =18, 30 and 42mm, respectively.

Nickel wire was uniformly oxidized and embedded in the aluminum matrix without fracture. When the material was evaluated as a temperature sensor, a temperature gradient was given on the specimen from heating side to cooling side and it was measured with an external thermocouple. Thermal electromotive forces generated between the embedded NiO/Ni fiber of length X=18, 30 and 42mm and aluminum matrix were also measured to obtain the temperatures. These values were compared with each other at the each position. The material was evaluated as a strain sensor by measuring the electrical resistance change of the embedded fiber during tensile test. Aluminum tabs of 0.5mm thick were put on both ends of the specimen to adjust the gauge length as 20mm. A tensile test was carried out by an Instron-type tensile test machine under the constant crosshead speed of $2\text{x}10^{-3}$mm/s. The strain of the specimen was measured by using a strain gauge. Electrical resistance change of the embedded NiO/Ni fiber was monitored during the tensile testing.

The results of temperature measurements of the specimen are summarized in Figure 11. The curve in this figure indicates the temperature gradient. The temperatures of the specimen surface at the positions of the embedded NiO/Ni fiber sensor, that is, at x=18, 30 and 42mm are indicated by the arrows. The temperatures resulting from the thermal electromotive forces generated between the embedded NiO/Ni fiber and the aluminum matrix at X=18, 30 and 42mm are shown by the open circles in the same figure. These values coincide well, which indicates that the embedded NiO/Ni fiber is working as a temperature sensor.

The relation between tensile strain in the composite and electrical resistance of the embedded NiO/Ni fiber was obtained by tensile testing. The electrical resistance increases linearly with increasing the tensile strain up to around 0.018. So, it is clear that the NiO/Ni fiber is working as a strain sensor in the aluminum matrix. The increase of the electrical resistance from the strain of 0.018 was caused by the debonding of the NiO/Ni fiber from the aluminum matrix, which could be improved by modifying its shape.

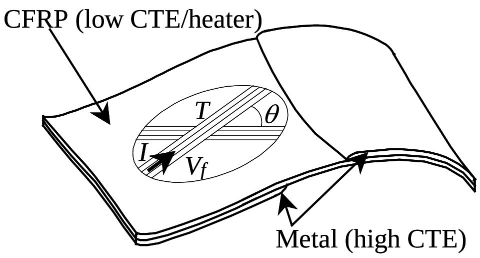

Fig. 12 The CFRP/metal active laminate.

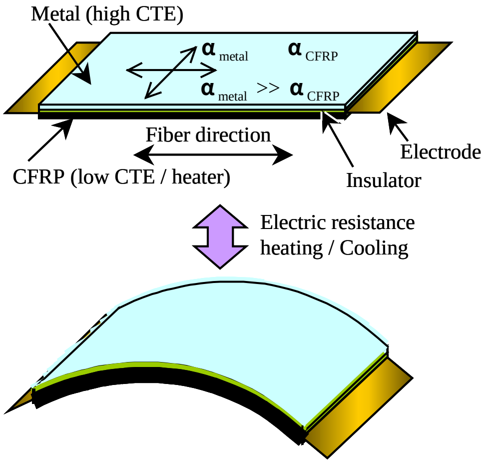

Fig. 13 An example of the CFRP/metal active laminate.

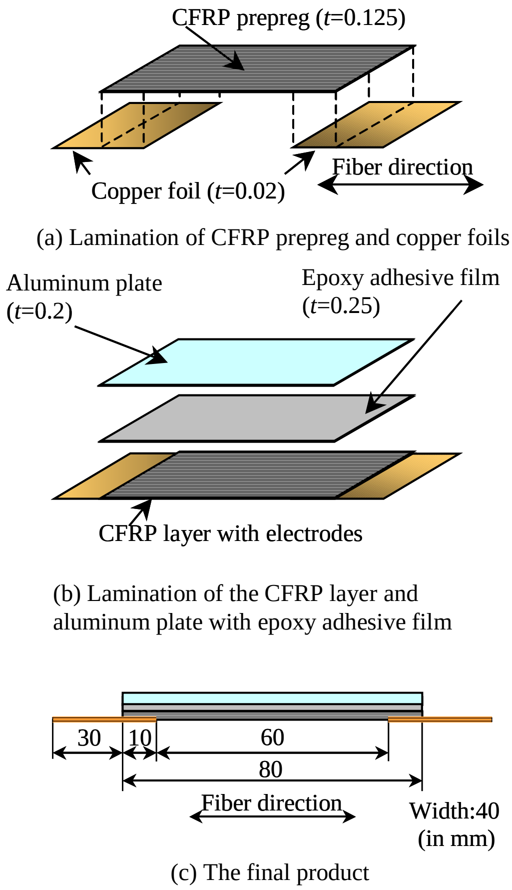

Fig. 14 Lamination of the materials.

According to these results, a single NiO/Ni fiber embedded in aluminum works as both a temperature and a strain sensor. When it was embedded in a SiC fiber reinforced aluminum composite, it could pick up breakages of the SiC fibers during tensile test. So it is useful for monitoring the condition of aluminum-based materials and composites.

Active Composites

Composite materials for structural use, especially fiber reinforced type composite materials, have been basically designed to suppress thermal deformation as well as to obtain better mechanical properties. But, as shown in Figure 2, the author proposed a new idea to regard it as an active structural material due to its thermal deformation. See Figure 12 for a proposed carbon fiber reinforced plastic (CFRP)/metal active laminate. The most simple and useful example of this type of material is shown in Figure 13 [7-9]. The mechanism of its actuation is fundamentally the same as that of bimetal, but its major advantage is its directional actuation due to directionality of the reinforcement fiber and the anisotropy of its coefficient of thermal expansion (CTE).

This material was easily fabricated by laminating a CFRP prepreg on a metal plate with an epoxy adhesive film as an insulator and two pieces of coppers foil as electrodes as shown in Figure 14. The lamination of the CFRP prepreg and the copper foils was done by hot pressing at 453K, under 0.1MPa and for 7.2ks, and then it was laminated with the aluminum plate using the epoxy adhesive film by hot pressing at 448K, under 0.1MPa and for 3.6ks. The electrodes were connected to a power source, and the CFRP layer was heated by electric resistance heating.

Curvature of the laminate r^{-1} decreased when it was heated and r^{-1} became zero when it reached its hot-pressing temperature as shown in Figure 15. Shapes of the CFRP/Al active laminate at room and hot-pressing temperatures are given in Figure 16. It could perform unidirectional actuation.

The fiber-optic sensor shown in Figure 3 was multiply made in the CFRP layer to enhance total optical loss when the active laminate is actuated [10]. This type of laminate was made as shown in Figure 17. Schematic diagram of the curvature and optical loss measurement set-up is shown in Figure 18. The laminate was put on a block and its embedded optical fiber was connected to a laser diode light source of 0.67×10^{-3}mm wavelength and to a power meter. The optical

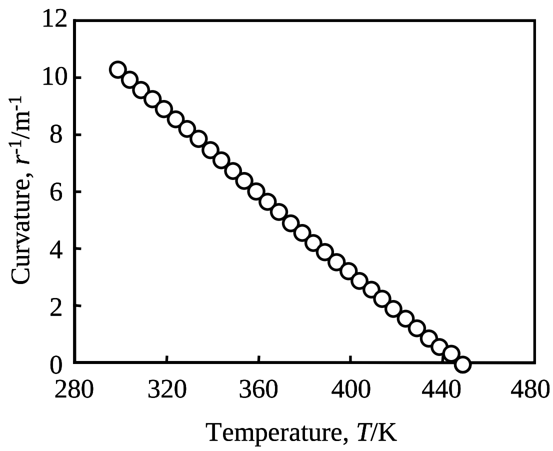

Fig. 15 Effect of heating temperature on curvature of the active laminate.

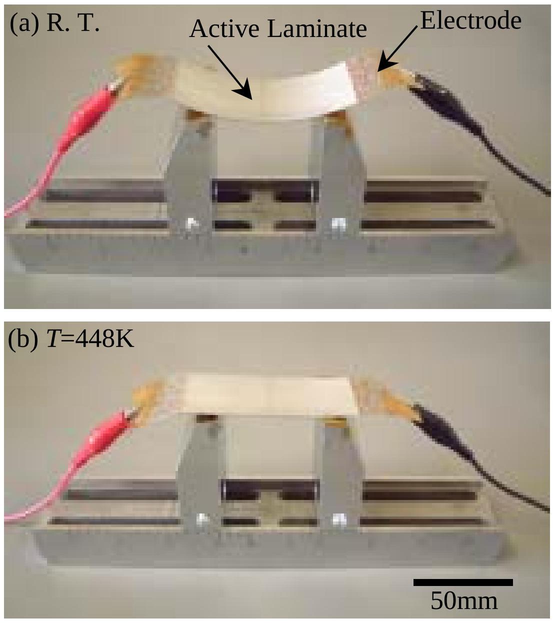

Fig. 16 The curvature of the CFRP/Al active laminate at (a) room temperature and (b) 393K.

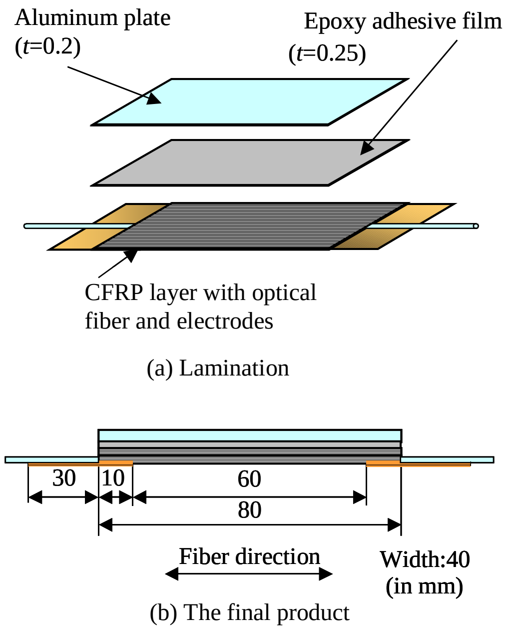

Fig. 17 Lamination of the CFRP layer with the other materials to form an active laminate with embedded optical fiber sensor.The dimensions of materials are also shown.

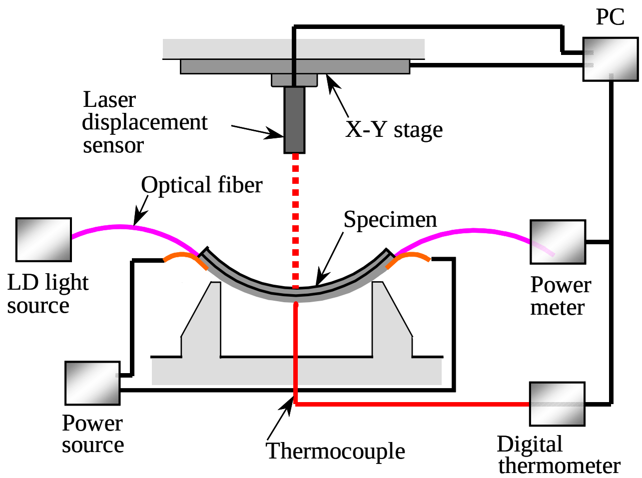

Fig. 18 Schematic diagram of the optical loss measurement system.

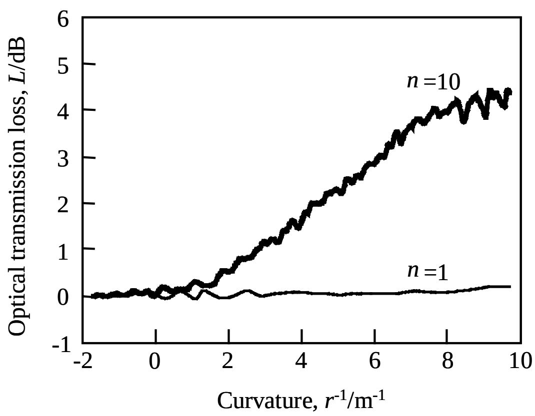

Fig. 19 Effect of fracture number n of embedded optical fiber on the relation between curvature and optical transmission loss of the active laminate.

loss variation was monitored during the curvature change of the laminate. In Figure 19, the effect of fracture number n of the embedded optical fiber on the relation between curvature r^{-1} and optical transmission loss L of the laminate is shown. According to this figure, the L as a function of r^{-1} is clearly increased by the increase in number n from 1 to 10. So the multiple fracture of the embedded optical fiber at its notches is effective to form a sensitive sensor for curvature monitoring of the laminate and will be useful for its shape control.

Conclusions

New concepts the author has proposed and demonstrated to realize metal and polymer based sensitive and/or active structural material systems suitable for health monitoring and/or active shape control are introduced in this paper. Most of the developments have been done by simple and innovative methods without using sophisticated and expensive sensors and actuators. The following topics were mainly examined.

(1) Formation of optical interference and loss type strain sensors in epoxy matrix and CFRP simply by embedding notched optical fiber and fracture of it in them. This type of sensor is simple, compact, robust and low cost. In the case of single notched optical fiber, an optical interference type sensor to detect small and precise strain was easily formed. In the case of multiply notched one, an optical loss type sensor for measurement of large strain was easily obtained.
(2) Fabrication of a multifunctional sensor for aluminum and its composite to monitor their temperatures, strains, fracture processes, and so on. It was successfully made by embedding an oxidized nickel fiber (NiO/Ni composite fiber) in them. A part of the oxide was removed before embedment to make a metallic contact between the nickel fiber and aluminum matrix to generate thermal electromotive force for temperature measurement. Strain was reflected on electrical resistance change of the embedded fiber. This type of sensor is also very simple and low cost.
(3) Development of active and sensitive composites for active shape control, and so on, using conventional structural materials as follows: An active laminate of CFRP (works as "bone" and "blood vessel") / epoxy (as insulator) / aluminum (as "muscle") / electrode (to apply voltage on CFRP), of which unidirectional actuation was realized by electrical resistance heating of carbon fiber in the CFRP layer and its curvature change could be monitored using optical fiber multiply fractured in the CFRP layer (works as "nerve").

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